

JOURNAL OF THE ROYAL SOCIETY OF WESTERN AUSTRALIA,
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ITS USE AS A BUILDING STONE

by

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I.—INTRODUCTION.

The limestone concerned with in this paper occupies hills and ridges, slightly elevated above the Swan Coastal Plain, running parallel to the west coast of Western Australia. The principal localities in which the stone is quarried are shown on the sketch map (Plate I.). Although it is called

* This paper was prepared during the tenure of a Hackett Studentship in the Department of Geology, University of Western Australia.

Catalogue	Number of Sample.		Quarry No.	Locality.
9223 (a) and (b)	1	A
9389, 9390	2	
9391, 9392	3	
9224, 9225, 9226, 9227	4	B
9399	5	
9235, 9236	6	C
9237, 9238, 9239	7	
9386, 9385, 9387, 9388	8	D
9395, 9396, 9397, 9398	9	
9228, 9229, 9230	10	E
9231, 9232, 9233	11	
10486	12	F

In collecting samples I am indebted to K. C. Tiller of the Education Department, who motored me to the various quarries and, in addition to help in the field, kindly lent me his thesis entitled "The Sedimentary, Engineering, Building and Ornamental Stones of the South-West Geological District." I am also indebted to Messrs. A. T. Brine & Sons, Contractors, who have given me permission to use their compressive strength data.

The laboratory work, with the exception of the compressive strength tests, was carried out in the Department of Geology, University of Western Australia, under the supervision of Professor E. de C. Clarke, to whom I am greatly indebted for suggestions and advice.

II.—MODE OF OCCURRENCE.

The coastal limestone in the vicinity of the Swan River was described over one hundred years ago by the Rev. Archdeacon Scott (1831, p. 320). An abstract reads as follows:—

The author, who was accidentally detained at the settlement recently established on the western side of Australia, describes a line of coast of more than thirty miles in length, composed of a highly calcareous sandstone, presenting very similar mineralogical characters throughout its whole extent. At a promontory about five miles to the north of the river Swan the calcareous sandstone exhibits a surface in which are numerous concretions having the appearance of enclosing vegetable matter. This character is by no means confined to this spot but is very commonly observed; and on a rising ground to the east of the space marked out for the intended town of Fremantle, the sandstone assumes the appearance of a thick forest cut down about two or three feet from the surface, so that to walk on it becomes extremely difficult and even dangerous.

The south coast of Garden Island presents a typical example of what Scott noticed near Fremantle. I visited Garden Island in 1930, prior to reading Scott's paper, and was particularly impressed by the stump-like appearance of the limestone, some of the "stumps" measuring about three feet in height and two feet in diameter, with perceptible widening at the base.

However, when quarried the coastal limestone presents a different aspect. In most quarries there are several types of material as follows:—

- (1) Capstone, a hard crust in layers more or less parallel to the surface, quite frequently covered or partially covered with soil;
- (2) Root-like tubes of stone irregularly ramifying in all directions. The constituent "roots" are roughly cylindrical, usually about $\frac{1}{2}$ inch in diameter, and in between them is loose calcareous sand. The term "*network*" is suggested for this structure;
- (3) Trunks or large pipes, cylindrical or slightly tapering bodies (made up of hard stone somewhat similar to the capstone), essentially straight and vertical and of some size—up to one foot in diameter. They always extend right up to the surface;
- (4) Bedded stone which alone is quarried for building purposes.

There are two types of quarry along the coast between Balcatta and Coogee, one type consisting of capstone, bedded stone containing organic matter and bedded stone devoid of organic matter; and the other consisting of capstone, network and bedded stone without organic matter. I think that the two types of quarry represent two stages in the development of the limestone. In the first type organic matter is present; in the second type the

organic matter has been completely removed and the roots have been petrified. The terms "juvenile" and "mature" are suggested for the first and second types respectively (Fig. 1).

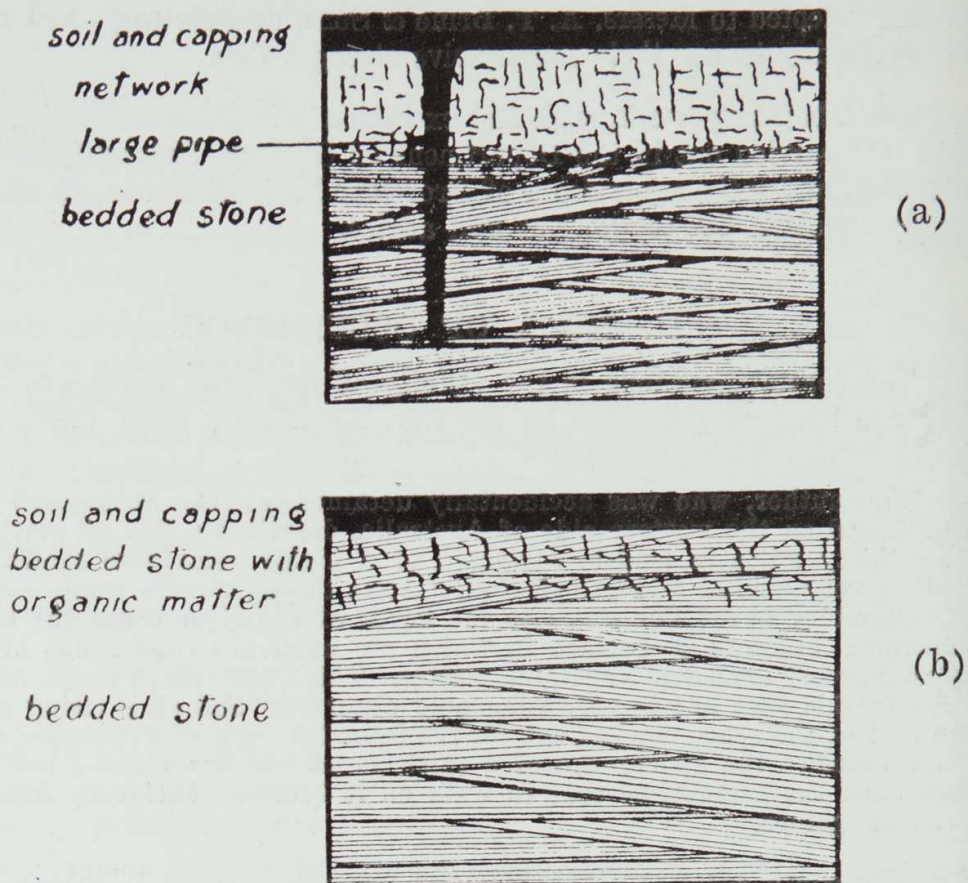


Fig. 1.—Diagrammatic representations of Mature and Juvenile types of quarry. (a) Mature Type, Quarry No. 8, locality D; (b) Juvenile Type, Quarry No. 3, locality B.

The depths of the zones below the surface are extremely variable. Descriptions of several quarries may serve to indicate the degree of variation.

Quarry No. 6, locality C, a typical example of a mature quarry, consists of capstone, network and bedded stone. The capstone and soil are about a foot or two in thickness, and they are immediately followed below by the network which in one place extends down to the base of the quarry (some twenty feet or so), and in other places extends to a depth of about twelve feet below the surface. This zone consists of a network of small, more or less cylindrical tubes, about $\frac{1}{2}$ in. in diameter, which are quite hard and dense. They have been built up by concentric shells or cylinders of carbonate of lime. Some of them contain definite air-passages through their centres, and in several, thin thread-like carbonaceous fibres form the central cores around which the carbonate of lime has been deposited. The presence of small black specks, seen quite clearly in end-sections of the tubes, suggests organic matter. The spaces between tubes are filled with incoherent sandy material.

The network in Quarry No. 8, locality D, is similar to that in Quarry No. 6, locality C, and the zone occupies a few feet in depth in most places, whilst in an old quarry face it extends down some 12 to 15 feet to the base of the quarry. There is also a trunk or large pipe which penetrates the bedded stone (Fig. 1 (a)).

Quarry No. 3, locality B (Fig. 1 (b)), is typical of the juvenile type. The overburden in the quarry is very small, practically amounting to a thin veneer of capstone and soil; but for three or four feet from the surface excellent quality stone is everywhere penetrated by roots and decayed organic matter which render it useless as a building stone. Network and pipes are completely absent.

Quarry No. 4, locality B, is another juvenile type. The capstone outcropping at the surface through red soil, extends down to a depth varying from one foot to about ten feet in the form of huge pipes surrounding organic matter. The network characteristic of the mature type of quarry is completely absent.

Beneath the capstone in the juvenile type, and beneath the network in the mature type of quarry is the bedded (current-bedded) stone. The current-bedding is of two types, large scale current-bedding in which the bedding is uniform over large distances (30 feet or more), and small scale current-bedding in which the bedding changes its direction within a foot or so. Many blocks of stone, 3ft. x 2ft. x 2ft. in size, with only one bedding plane may be quarried from the large scale type, whilst in a single block of the same size from the small scale type there may be many changes in the direction of the bedding planes.

Both large and small scale current-bedding may be observed in any one quarry irrespective of whether it belongs to the juvenile or to the mature type. The stone from large scale current-bedding is usually of a better quality than small scale current-bedded stone, but this is not general, for in one quarry (quarry No. 7, locality C), some of the finest "shoddies" (*i.e.*, carefully selected blocks of stone) contain small scale current-bedding. On the other hand, in quarries where large quantities of powder are used in blasting, small scale current-bedded stone is invariably shattered and is therefore useless as a building stone. Quarry No. 3, locality B, is an example of this, but I believe that the waste so produced is used for road construction.

In some quarries bedding planes are very well marked, whilst in others no bedding planes can be seen.

III.—PETROLOGY.

A GENERAL DESCRIPTION.

Macroscopic.

The colour of the coastal limestone varies from pale ash-grey, through white and cream to buff, depending to some extent upon the nature of the constituents. The white, cream and pale buff stones are usually soft and chalky, or soft and spongy, whilst the more coloured varieties are hard, slightly brittle and very rarely spongy. The colour appears to be largely influenced by the grain of the stone, for the white stones are as a rule extremely fine grained, composed of finely divided calcium carbonate which rubs off easily as a chalky powder, whereas the coloured stones are made up of white, yellow, brown, red and violet shell fragments, with waxy and frosted grains of quartz.

All stones can be cut with an axe but with different degrees of ease. Some of the very hard buff coloured stones give a metallic ring when struck with a hammer, while the soft white stones emit a dull thud. The white chalky or spongy stone is largely in demand for bungalow foundations, principally because it can be shaped readily with an axe.

Microscopic.

The principal constituents of the coastal limestone revealed by the microscope, are fragments of calcium carbonate, quartz grains and a cement of calcium carbonate. Occasionally grains of felspar (microcline, orthoclase and plagioclase) can be seen, and in one section a grain of epidote was noticed. Rutile needles are very abundant as hair-like inclusions in the quartz grains. Minerals apart from quartz and felspar are thus rare, but in a sample of stone from Cape Leeuwin, a large assemblage of minerals was noted, in which were included quartz, felspar (several varieties), hornblende, ilmenite, magnetite, garnet, apatite and augite.

The carbonate fragments consist of small shells or parts of shells, and opaque grains in which shell structure cannot be seen. The shells are mostly foraminiferal tests (whole or fragmentary) and oval-shaped mollusc fragments. An occasional sponge spicule occurs. Among the foraminifera are forms resembling *Discorbina*, *Miliolina*, *Textularia*, *Cristellaria* and *Globigerina*. The size of the carbonate fragments varies from less than 0.01mm. up to 2mm. in diameter. It is usual to find that the shell fragments in stone from the mature type of quarry are less well preserved than those in stone from the juvenile type of quarry.

The quartz grains are rounded to angular and vary greatly in size, the smallest being less than 0.01mm. and the largest measuring up to 2mm. in diameter. The largest grains are invariably well rounded, while the smallest are angular. Medium-sized grains have no definite shape (Fig. 2).

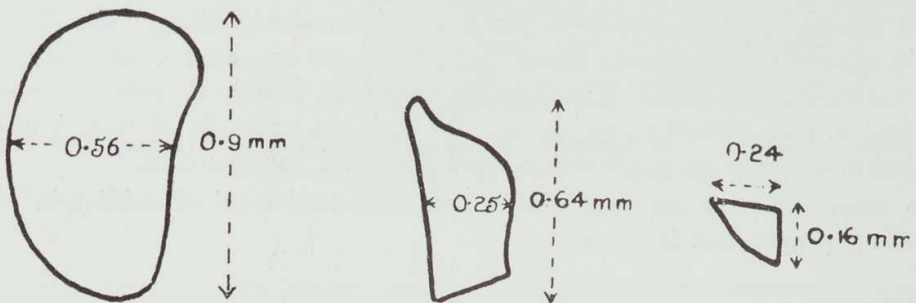


Fig. 2.—Typical quartz grains.

The cement varies considerably in distribution. In some stones it acts as a definite matrix binding the shell fragments and quartz grains together, but in others the shell fragments are fused to each other by a thin film of cement which is continuous with, and part of, each shell fragment. The cement appearing as a matrix is made up of minute grains of calcium carbonate, not in crystalline continuity. Usually it is very irregularly distributed. In some stones it forms a fairly thick layer around quartz grains, especially very large grains, whereas the shell fragments possess mere films of cement. In other stones, both quartz grains and shell fragments are liberally coated with cement. In all stones, however, there is never a complete filling of the spaces between the grains. There are thus many air spaces which account for the high porosity of the stone. The amount of air space depends on the closeness with which the grains are packed and the nature and distribution of the cement. It is therefore convenient to describe the various types of stone under the heading of "Textural Types," and as will be shown later, the hardness, density and porosity of building stones of the Swan Coastal type, depend largely on texture.

B TEXTURAL TYPES.

Under the heading of texture are considered the size and shape of the individual grains, their relationship to each other and the nature and distribution of the cement. The most noticeable differences in the coastal limestone are, however, the size of the grains and the closeness of packing and consequently the stones are dealt with under these headings.

It must be emphasised here that in all stones, irrespective of grain size, no hard and fast lines can be drawn between those in which the grains are closely packed together and those in which the grains are widely separated, for there is every perceptible gradation between the two. It is however convenient to divide the stones into two types, close grained and open grained, which represent the two extremes of texture.

It is usual to find that stones from the mature type of quarry, where networks are abundant, are open grained, and the shell fragments found in these stones are less well preserved than those found in the juvenile type of quarry. The cement, though patchy, is more abundant in "mature" stone than in "juvenile" stone, where the cement usually amounts to a mere film coating the grains rather than a definite filling or matrix. Suggested explanations for the differences between the stones selected from the two types of quarry will be given in another section of this paper (p. 40).

1. FINE GRAINED STONES.

(a) Close Grained.

Textural Type 1a.

The best example of a stone of this type is 9237 from a "shoddy" in Quarry No. 7, locality C. The stone is fairly compact, fine and even in grain, and is of a cream to pale buff colour. It is neither spongy nor friable, but is nevertheless very easy to shape. Bedding planes are well pronounced, even in a small 2in. cube block.

The even grained appearance of the hand specimen is very clearly seen under the microscope (Plate II., 1a.). Both quartz and carbonate grains are very tightly packed together. The quartz grains are irregular in shape but remarkably uniform in size. The largest grains do not exceed 0.25mm., while many do not exceed 0.16mm. Very small grains, 0.08mm. or less are also particularly abundant, but none of the grains are rounded. A few grains of feldspar and an occasional grain of hornblende complete the mineral content of the stone.

The most striking feature of many of the fragments is their elongation along a direction more or less parallel to the bedding planes. Most of them are of molluscs but some appear to be sponge spicules. Foraminiferal tests are fairly rare, those present being difficult to identify.

The cement is distributed evenly throughout the stone as a mere film surrounding quartz grains. The carbonate fragments appear to be fused to each other, but where joined to quartz grains small bridges of cement are usually seen. Fig. 3 shows the way in which the grains are cemented.

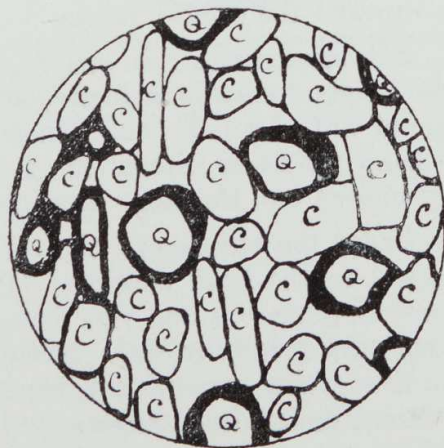


Fig. 3.—Nature of the cement in 9237 (Quarry No. 7, locality C).

Q, quartz grains; C, carbonate grains; cement is black. X about 30.

Under the high power the cement is seen to consist of finely divided calcium carbonate. This material rubs off the hand specimen as a chalky powder, but a magnification of 300 diameters produced by a high power objective shows it to consist of extremely minute grains.

Another stone belonging to this type is 9227 from Quarry No. 4, locality B. It is a very hard fine grained stone, efficiently cemented, and has the appearance of a hard sandstone. It is a little coarser in texture than the locality C stone described above. Quartz grains are comparatively few in number but they vary greatly in size and shape, only the large grains showing rounded forms. Though most of the grains are from 0.15 to 0.3mm. in diameter, there are a few very large ones (the largest measuring 1.5 x 0.65mm.) and some very small ones less than 0.1mm. in diameter.

A few grains of feldspar are seen occasionally, and rutile needles are sometimes noticed as inclusions in quartz grains.

The carbonate fragments consist mainly of foraminiferal tests, many of which are well preserved, with a few fragmentary molluscs and a few opaque grains. All grains are closely bound together by a cement of calcium carbonate which is plentifully and evenly distributed. Two main differences can be observed between the nature of the cement in this and the stone from locality C. The first is that in this stone both quartz and carbonate grains are enclosed in the cement whereas in the locality C stone the quartz grains are cemented to each other and to the carbonate grains by a film of cement whilst the carbonate grains appear to be fused to each other. In other words the cement is confined to the quartz grains in the locality C stone, but in this stone it is shared alike by quartz and carbonate grains. The second difference is in the nature of the cement. As in the stone (9237) from locality C. the cement is granular, but the grains are very much larger and they appear to be definitely of crystalline calcite. The differences in hardness and porosity are probably due to these differences in the nature of the cement, for the locality B stone is very much harder than the locality C stone and it has a lower porosity. The question of differences in coherence will be discussed in another section of this paper.

(b) Open Grained.

Textural Type 1b.

The best example of this type comes from Quarry No. 6 locality C. The quarry belongs to the mature type in that it has the network between the cap and the bedded stones.

The stone from this quarry is very soft, friable and spongy, and its light weight indicates a high porosity. The colour is cream with a faint tinge of buff. It is a fine, even-grained stone and no quartz can be seen in the hand specimen without the aid of a powerful lens. The air spacing is very uneven and the stone appears to be very loosely coherent.

Under the microscope the texture is seen to be not nearly as even as it seems in the hand specimen (Plate II., 1b.). The quartz grains are extremely numerous and very irregular in shape (mostly angular), but they do not vary greatly in size. Large grains are absent and with the exception of a few grains measuring 0.5mm. in diameter, the grains are of the order of 0.2mm. or less in diameter.

The carbonate fragments are made up of opaque grains, transparent grains of calcite, and ill-defined shelly material of a very fragmentary nature;

and more or less evenly distributed among them are the quartz grains. The shell fragments are usually poorly preserved and recognition of the varieties is rather difficult. All fragments whether quartz or carbonate are fairly widely separated from each other by a non-plentiful and totally inadequate cement of calcium carbonate, leaving wide and irregular inter-granular air-spaces. In rare instances, the cement completely fills the spaces between grains, and unlike stone from quarry No. 7 (same locality), the cement is distributed around quartz and carbonate grains alike.

The cement is of the very finely divided type mentioned previously in connection with stone from the other quarry in this locality, and it seems quite general that the finely divided cement is characteristic of the mature type of quarry.

The stone from quarry No. 3, locality B, is another open grained stone but it differs in many ways from the stone in quarry No. 6, locality C. The quarry belongs to the juvenile type, and is made up of a thin veneer of soil and capstone followed by a zone of bedded stone containing organic material but no large pipes or network. The bedded stone is buff coloured, fine and even grained, moderately hard but a little spongy.

Under the microscope the stone is seen to be fairly even grained, most of the grains being about 0.3mm. in diameter. Mineral constituents (i.e., those other than carbonate) are not very abundant and consist almost entirely of angular quartz grains, with a few rounded grains here and there. The maximum variation in size of the quartz grains is 0.03 to 0.6 mm. An occasional grain of epidote and felspar can sometimes be seen.

The carbonate fragments consist principally of well preserved shells such as molluscs and foraminifera, with rounded or elongated opaque grains. The average size of the carbonate fragments is about 0.3mm., but larger ones (one of which measured 0.16 x 1.13mm.) are not uncommon.

The grains are usually not in contact with each other but are separated by a fairly coarsely granular cement of calcium carbonate which embeds both quartz and carbonate grains alike. This cement is fairly evenly distributed throughout the stone. Fig. 4 illustrates the relationship of the grains to the cement.

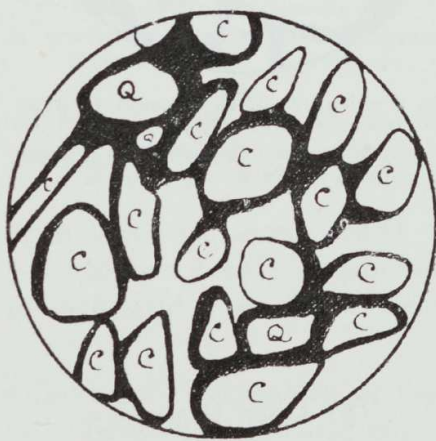


Fig. 4.—Nature of the cement in 9391 (Quarry No. 3, locality B).

Q, quartz grains; C, carbonate grains; cement is black. X about 30.

2. MEDIUM GRAINED STONES.

(a) Close Grained.

Textural Type 2a.

9398, Quarry No. 9, locality D, analysed by Coalstad and petrographically examined by Hobson, is the best example of this type of stone. It is a dense hard stone, with an even, medium grain, consisting of rounded shell fragments, many of which are salmon-pink and brown coloured, and rounded, frosted grains of quartz.

Under the microscope the stone is seen to be fairly even grained, the quartz grains showing a greater range in size than the carbonate grains. Quartz is fairly common and occurs principally as angular or sub-angular grains, with very few of the large grains rounded or oval-shaped. They vary in size from 0.05 to 1mm., with an average size of 0.5mm. A few large grains of feldspar are also present.

The carbonate fragments are mostly 0.4 to 0.5mm. in diameter with very few exceeding 0.5mm. They consist of fairly well preserved foraminiferal tests, fragmentary molluscs and opaque grains which cannot be recognised as shelly material.

All grains are closely packed together, nearly all touching and are well cemented. The cement is fairly evenly distributed, but is usually more abundant around quartz grains than around carbonate fragments. It is the very coarsely granular type of cement which appears to be characteristic of hard stones.

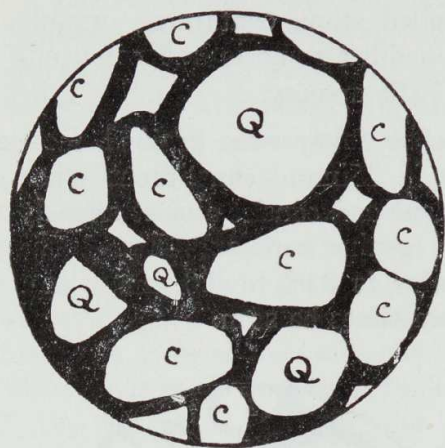


Fig. 5.—Nature of the cement in 9398 (Quarry No. 9, locality D).

Q, quartz grains; C, carbonate grains; cement is black. X about 30.

This sample (9398) was taken from the sea-wall where it had been exposed to the weather for over sixty years. Originally it came from quarry No. 9, loc. D. Hobson made three sections of the stone, one from the outside, weathered face, and two from the interior. The latter are better cemented than the outside one in that the cement is more plentiful, and the grains are more closely and efficiently held together.

Other stones belonging to this type are 9395, 9396 and 9397 from the same quarry (No. 9, locality D), and some samples obtained from Garden Island, which are a little finer in grain.

(b) Open Grained.

Textural Type 2b.

The stone from Quarry No. 1, locality A, selected as an example of this type, is a faint buff-tinged stone with medium grain. Examination with a hand lens shows that the grains are not of uniform size. Quartz grains are particularly abundant and vary in size from less than 0.01mm. up to 1mm. in diameter. They all have a frosted appearance which is probably due to wind abrasion. The carbonate fragments are often pale brown in colour and do not show as much variation in size as the quartz grains. The average grain size is about 0.5mm.

The constituents of the stone seen under the microscope, are quartz grains and occasional fragments of feldspar, carbonate grains (mostly tests of foraminifera and fragments of mollusc shells) and a carbonate cement.

The most striking feature observed in the thin section is the irregular grain due largely to the extreme variation in size of the quartz grains (Plate II., 2b.). In the best quality stone the large quartz grains average 0.7mm., and the smallest ones vary from 0.08mm. to 0.3mm. In general, only the very large grains (sometimes 1mm. or more in diameter) are rounded. The very small ones are angular and the medium size grains (0.2 to 0.7mm.) are sub-rounded. A few of the large quartz grains contain rutile needles (sagenite webbing).

The carbonate fragments are of two types, one type showing definite shell structure and the other, owing to opacity, showing no recognisable structure. The carbonate grains are rounded, elongated or oval-shaped, rarely angular.

The cement, which is of the very fine granular type, is very irregularly distributed throughout. The carbonate grains are practically devoid of cementing material and, where in contact with each other, they appear to cohere by only a very thin film, which represents the fringed boundaries of grains which have started to dissolve. On the other hand quartz grains frequently have thick coatings of cement (Fig. 6).

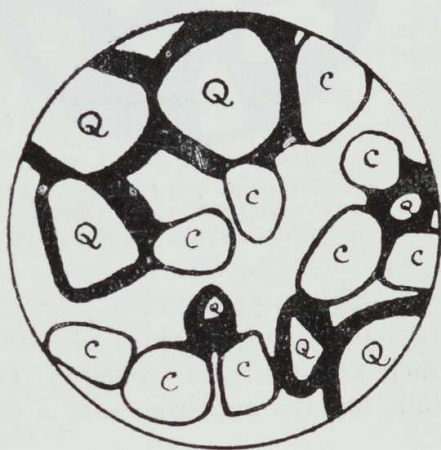


Fig. 6.—Nature of the cement in 9223 (Quarry No. 1, locality A).
Q, quartz grains; C, carbonate grains; cement is black. X about 30.

Another stone of this type was obtained from Quarry No. 11, locality E. This stone is similar in texture but a little harder and more efficiently cemented than 9223 (Quarry No. 1).

3. COARSE-GRAINED STONES.

Textural Type 3.

Only two (9400 and 9401) out of about forty different samples of limestone examined were found to be coarse grained. Both samples should strictly be regarded as sandstones, for their silica contents are over 50 per cent.

9400 is a very soft, white stone, containing rounded, waxy grains of quartz embedded in a white chalky matrix. The stone is easily shaped and when rubbed between the fingers disintegrates readily into quartz grains and chalk powder.

Under the microscope it is seen to consist principally of very large rounded, oval shaped or elongated quartz grains, and a few large shell fragments embedded in a finely divided spongy cement. The large quartz grains, some of which contain sagenite webbing, range in size from 0.5 to 2mm. A few small grains 0.1mm. and less in diameter are also present. Felspar is not plentiful, but a few large grains 1mm. in diameter can sometimes be seen. Shell fragments are very large but not abundant. They are mostly elongated or oval-shaped, and they appear to be principally

mollusc remains. The cement fills in the spaces between all grains but it is porous, and is very finely divided (Fig. 7).

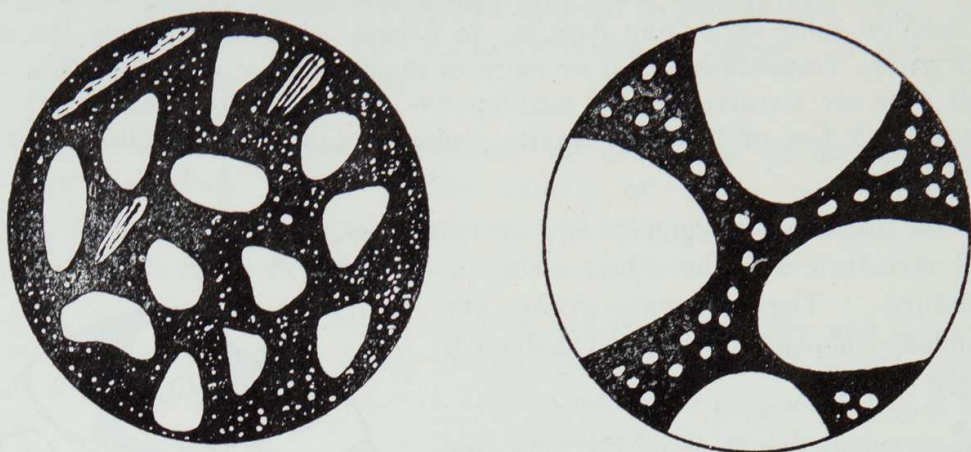


Fig. 7.—Nature of the cement in 9400. (a) \times about 8, (b) \times about 30. Quartz grains are colourless, shell fragments striped. The cement (black) is porous, the tiny colourless specks representing pore spaces.

9401 is very unlike 9400 in hand specimen. It is composed of large rounded, frosted grains of quartz, white, brown and salmon-pink coloured shell fragments, all cohering, apparently, without the aid of a cement. It thus has the appearance of a consolidated, coarse beach sand.

Under the microscope it is seen to differ from 9400 in that there are more shell fragments, all grains being more tightly packed together, many touching each other, and in that the cement is less abundant and less porous. Of these differences, which are undoubtedly responsible for the difference in the appearance of the hand specimens, the proportion of carbonate fragments to cement is probably the most striking. The two stones have approximately the same porosity and insoluble content, but whereas in 9400 most of the soluble material (principally carbonate) is in the form of cement, in 9401 it takes the form of shell fragments.

IV.—LABORATORY DETERMINATIONS.

A—POROSITY.

In this paper the porosity of a stone is expressed as the percentage by volume of air-space, calculated on moisture-free stone. The method of determination employed is briefly as follows:—

A block of stone about 4 cubic inches in volume is dried at 130° C. and water slowly added until the water level is about $\frac{1}{4}$ inch above the top of the block. The water is boiled for twenty minutes, and the boiling repeated twice at intervals of twenty-four hours. The block is then suspended from the arm of a balance by a thin thread and weighed under water. It is then removed from the water, dried quickly with some absorbent material, and weighed on a clock glass. It is then dried again at 130° C. and reweighed. The difference in weight (usually very small) at the commencement and at the end of the experiment gives the amount of material detached from the stone during boiling, handling and drying. Corrections are made for the amount of detached material. From the data so obtained, the porosity, bulk density and the density of the material in the stone are calculated.

In obtaining the density of the material in the stone, a check on the accuracy of the experiment is obtained.

Example:

Estimation of Porosity, etc.

Locality :	B, Quarry No. 3.
Sample No. :	9392.
Treatment :	Preliminary and final drying (130° C., 4 hrs.)
Weight of block	101.17 gm. (prel. drying) ; 101.15 gm. (final drying).
Weight of water-logged block under water ...	63.83 — .08 (Wt. of thread) gm.
Weight of water-logged block in air ...	136.35 gm.
Weight of water absorbed	35.18 gm.
Volume of water absorbed	35.18 ml.
Volume of material in block	101.17 — 63.75 = 37.42 ml.
Total volume of block	72.60 ml.
Porosity $\left[\frac{\text{Vol. air-space} \times 100}{\text{Total volume}} \right]$	$\frac{35.18 \times 100}{72.60} = 48.5 \%$
Bulk Density $\left[\frac{\text{Wt. of stone}}{\text{total volume}} \right]$	$\frac{101.17}{72.60} = 1.39$
Density of Material $\left[\frac{\text{Wt. of stone}}{\text{vol. material}} \right]$	$\frac{101.17}{37.42} = 2.70$

The value of 2.70 for the density of the material of the block is roughly a constant for most of the coastal limestones. It does vary slightly, from 2.68 to 2.72, depending on the insoluble percentage. In this instance the stone contains 17 per cent. silica (S.G. = 2.65) and 83 per cent. carbonate (S.G. = 2.175). The density of material in these proportions, calculated from the Specific Gravities given, is 2.70.

Compared with the average limestone found in England, the coastal limestone is a very porous stone. Forty samples tested gave a range in porosity from 17 per cent. to 57 per cent., with an average value of about 40 per cent. On the other hand, limestones from England give an average value of about 20 per cent., with values in some stones, as low as 8 per cent. The least porous stones of the coastal limestone type have therefore approximately similar values to those of the most porous stones found in England. Table 2 shows the number of stones tested with their ranges in porosity.

TABLE 2.

Number of Samples.							Range in Porosity.
1	...	...	...	...	...	...	Under 20 per cent.
4	...	...	...	...	...	...	20—30 "
12	...	...	...	...	...	...	30—40 "
13	...	...	...	...	...	...	40—50 "
7	...	...	...	...	...	...	Over 50 "

A very important feature of the coastal limestone is the nature of the pore spaces. From microscopic examination, and from the fact that the density of the material in the stone, calculated from the porosity data, is

fairly constant, it is obvious that the pore spaces are in direct communication with the atmosphere. Each pore space can therefore be occupied by water, so that weighing a block of water-logged stone under water is equivalent to weighing the same amount of powdered material in a density bottle; hence the constant density, 2.70. The importance of this will be shown in subsequent sections of this paper.

The facing stones most in demand are those whose porosities range from 35 per cent. to 45 per cent. For ordinary bungalow foundations, stones with values from 40 per cent. to 55 per cent. are used. Stones with values lower than 35 per cent. are rarely used because they are usually hard to shape.

The high porosity of the coastal limestone is due to the inadequacy of the cement. In many stones, coherence is obtained by thin films of cement which are really the recrystallised surface coats of carbonate grains which had commenced to dissolve in rain water containing carbon di-oxide. An explanation of the formation of the cement will be found in a subsequent section of this paper (p. 40). In other stones because of uneven grain the cement is very patchy (*e.g.*, the stone from locality A) and in two stones (9400 and 9401) the cement is abundant but is of a spongy nature.

In the following table (Table 3) are given the ranges in porosity of stones from various localities.

TABLE 3.

Locality.				Range in porosity.			Number of samples.
A	...	...	...	41—44%	...	...	4
D	...	...	...	24—51%	...	...	8
C	...	...	...	39—55%	...	...	5
E	...	...	...	35—55%	...	...	6
B	...	...	...	18—48%	...	...	7
Garden Island	...	...	...	25%	...	...	1

B INSOLUBLE CONTENT.

Like porosity, the acid insoluble content (commonly referred to as "sand") is extremely variable, ranging from 5 per cent. to 66 per cent. The average value, based on thirty-six analyses, is, however, only 23 per cent. The reason for such a low average is due to the fact that in most of the samples the insoluble content is under 30 per cent. Table 4 shows the number of samples analysed and the ranges in insoluble content.

TABLE 4.

Number of Samples.				Range in Insoluble Content.
20	...	...	...	Under 20 per cent.
8	...	...	...	20—30 per cent.
5	...	...	...	30—40 per cent.
3	...	...	...	Over 40 per cent.

Petrographic examination has shown that the insoluble material is almost entirely silica (quartz) and that the amount of heavy minerals is negligible. It has also shown that the reason for such a wide range in the insoluble content is due to differences in grain size. Stones with uneven grain, such as those from locality A, and coarse grained stones such as 9400 and 9401 have very high insoluble contents whilst fine grained stones (*e.g.*, those from locality B) have low insoluble contents.

Table 5 shows the range in insoluble content of stones from various localities.

TABLE 5.

Locality.			Range in Insoluble Content.			Number of Samples.	
A	...	...	31—50	per cent.	...	...	4
D	...	...	16—33	per cent.	...	...	8
C	...	...	12—29	per cent.	...	...	5
E.	...	...	8—21	per cent.	...	...	6
B	...	...	8—17	per cent.	...	...	7
Garden Island	...	...	5	per cent.	...	...	1

C.—COMPRESSIVE STRENGTH.

Tests for compressive strength of the coastal limestone have been carried out at the School of Engineering of the University of Western Australia during the course of erection of the Hackett Memorial Buildings, and I have obtained permission from Messrs. A. T. Brine and Sons, Contractors, to use the data obtained.

The range in compressive strength of the coastal limestone shown by over forty tests, is very great—from 10 tons and less per square foot up to 318 tons per square foot. However, stones with a compressive strength exceeding 150 tons per square foot are exceptional, and, as can be seen from Table 6, two-thirds of the samples tested gave values less than 30 tons per square foot. An approximate average value, based on samples of building stone commonly used, is 25 tons per square foot.

Table 6 shows the number of samples tested, with their ranges in compressive strength.

TABLE 6.

Compressive Strength. Tons/sq. ft.							Number of Samples.	
Under 20	12
20—30	16
30—50	2
50—110	5
100—150	5
Over 150	2

The variation in compressive strength values is due to variation in porosity, insoluble content and texture. The most resistant are fine or medium grained stones with low porosity and low percentage of insoluble material. Weak stones have high porosity values. Coarse grained stones are usually weaker than fine grained stones with the same porosity. A detailed account of the factors affecting compressive strength will be found on p. 33).

Table 7 gives the ranges in compressive strength of stones from various localities.

TABLE 7.

Locality.			Range in Compressive Strength. Tons/sq. ft.			Number of Samples.	
A	...	...	20—36	...	...	...	6
G	...	...	9—27	...	...	...	12
D*	...	...	34—318	...	...	...	9
B	...	...	21—31	...	...	...	6

* Of these samples, which originally came from Quarry No. 9, four were taken out of an old building, three were obtained from the sea-wall where they had been for over 60 years, and two were collected from the quarry in 1929.

V.—FACTORS AFFECTING THE PROPERTIES.

A—FACTORS AFFECTING HARDNESS.

The "hardness" of a building stone (*i.e.*, the ease or difficulty with which it is dressed to any required shape and size) depends largely upon two factors, the hardness of the component minerals and their state of aggregation. Merrill (1910, p. 33) states that "however hard the minerals of a rock may be, it appears soft and works readily if the particles adhere with slight tenacity. Many of the softest sandstones are composed of the hard mineral quartz, but the grains fall apart so readily that the stone is as a whole soft."

Most samples of the coastal limestone are of similar composition, so that the first factor, the hardness of the component minerals, is relatively unimportant. The difference in "hardness" must therefore be due to state of aggregation. If the grains are closely packed together and are efficiently cemented, the stone will have a low porosity and will be fairly hard. If, on the other hand, the grains are loosely held together, the stone will have a high porosity and will be fairly soft. Porosity is therefore to some extent a measure of "hardness." To test the accuracy of this statement I arranged Coalstad's samples in the order of their "hardnesses" and found that the arrangement fitted in well with their porosities. 9398 having the lowest porosity was the hardest stone; 9392 having the highest porosity was the softest. Here, then, are the answers to the questions (a) and (b) asked on p. 18. 9398 is harder than the other samples because it has the lowest porosity. Difference in porosity is not associated with difference in mineral composition, but is due to difference in the state of aggregation.

The state of aggregation is therefore the primary factor affecting the "hardness," and to account for differences in "hardness" and porosity, a detailed petrographic examination of the internal structure of the stone is necessary. This examination has been made and the types described in the petrological section of this paper. The diversity of these types is responsible for the wide range in porosity and "hardness." Thus we have fine, medium and coarse grained stones, some of which have their grains closely packed together whilst others have their grains comparatively widely separated. The cementing of the grains may be due to thin films of carbonate which coat each shell fragment, or thick patchy cement which binds some grains and not others; or again the cement may be plentiful but quite porous as in 9400 and 9401 (p. 27).

Porosity is to a large extent a measure of the "hardness," but some stones which are identical in porosity, composition and grain size, differ in degree of "hardness." This is particularly noticeable in average samples of stone from localities B and C. The locality B stone is much harder than the stone from locality C, to which it is similar in many respects. Petrographic examination has revealed a very important difference in the nature of the cement. The cement in both is not a homogeneous filling, but is granular (*i.e.*, composed of very fine grains of calcium carbonate closely bound together), but that of the B stone is much coarser and appears to be more crystalline than the cement in the C stone. The result is that the coarsely granular cement of the B stone has a greater binding power than the finely granular cement of the C stone which tends to decompose into gritty material and chalky powder. The difference in "hardness" of the two types of cement is probably due to the same factors which are responsible for the difference in

“hardness” of two stones of similar composition such as chalk and marble. The chalk is soft and powdery, and is made up of finely divided calcium carbonate, whilst the marble is hard and coarsely crystalline.

It is therefore possible to obtain a stone with a high porosity (say 46 per cent.) which is comparatively hard; and it is from the juvenile type of quarry (*i.e.*, where there is no network between the cap and bedded stones) that such a stone is usually obtained; on the other hand a softer stone with a lower porosity is usually obtained from the mature type of quarry.

B—FACTORS AFFECTING COMPRESSIVE STRENGTH.

The principal factors affecting the compressive strength are porosity, insoluble content and grain size. Stones with low porosity and insoluble content and fine or medium grain give high compressive strength values; stones with high porosity and insoluble content and coarse grain give low compressive strength values.

Table 8 shows the compressive strength, porosity and insoluble content of stone from various localities.

TABLE 8.

Sample.	Locality.	Quarry.	Compressive Strength.	Porosity.	Insoluble Content.
9398	D	No. 9	Tons/sq. ft. 150 276 318	23·6	19·67
9397	D	No. 9	129 143	25·6	16·25
9395	D	No. 9	112 79	29·8	25·44
9403	Taken out of an old building		70 65	32·8	30·31
9399	B	No. 5	111 59	37·4	14·37
9396	D	No. 9	52 34	41·2	18·15
9401	Taken out of an old building		41 23	35·2	66·81
Average sample	A	Nos. 1 and 2	27 average	41·0 average	38·00 average
Average sample	B.	No. 3	26 average	46·0 average	16·00 average
9402	Taken out of an old building		14 12	49·7	18·67
9400	do.	do.	*12	36·5	61·20

* This sample had an initial fracture and was not square.

From the above figures it is possible to draw up a table (Table 9) from which, given two of the three values, the third may be determined approximately.

TABLE 9.

Type.	Porosity (volume of air space).	Insoluble Content.	Compressive Strength.	Examples.	Quarry.
A1 	per cent. Under 25	per cent. Under 20	tons/sq. ft. Over 150	9398	No. 9 (loc. D)
A2 	25—30	Under 25	100—150	9395 9397	No. 9 (loc. D)
A3 	25—30	Under 30	75—100	9395	No. 9 (loc. D)
A4 	30—40	Under 30	50—75	9399	No. 5 (loc. B)
A5 	30—40	Over 30	} Under 50 {	Average stone do.	No. 3 (loc. B)
	Over 40	Under 30		9396	Nos. 1 and 2 (loc. A)
	Over 40	Over 30		9401 9400 9402	No. 9 (loc. C)
					Taken out of an old building

Unfortunately this table is not as useful as it may seem, because most of the stones used for building purposes belong to the type A5; but it serves to indicate that the compressive strength varies with porosity, insoluble content and grain size. It is possible, however, having obtained the porosity values and insoluble contents of stones of this type (type A5), to arrange them roughly in order of their compressive strengths, taking into account grain size and the nature of the cement, as well as porosity and insoluble content; and it is further possible to estimate roughly the compressive strength of each stone by comparing it with a stone which possesses similar characters and properties and whose compressive strength is already known.

C—FACTORS AFFECTING THE ACOUSTIC PROPERTIES.

Until recently the use of coastal limestone was restricted to exterior facings and foundations of buildings, but as sound-absorption tests showed that the Coogee stone possessed fairly good acoustic properties, the University authorities decided to line the Winthrop Hall with this stone.

In a large hall such as the Winthrop Hall, it is essential that the lining material should be a good absorber.

Sound incident on a material is reflected, absorbed and transmitted [as indicated in Fig. 8]. When such a material is installed on the walls of a room, its absorbing effect includes the transmitted sound as well as the pure absorption in the material. In this sense an open window is considered a “perfect” absorber, but it is really a perfect transmitter. The coefficients determined are based on this conception; that is, that what is not reflected is “absorbed.”

The open window is taken as the standard absorber with a coefficient of 1.00 or 100% absorption. A material in the room with a coefficient of 0.50 means that it absorbs 50% as much sound as an open window of equal area.—(Watson, 1927, p. 5.)

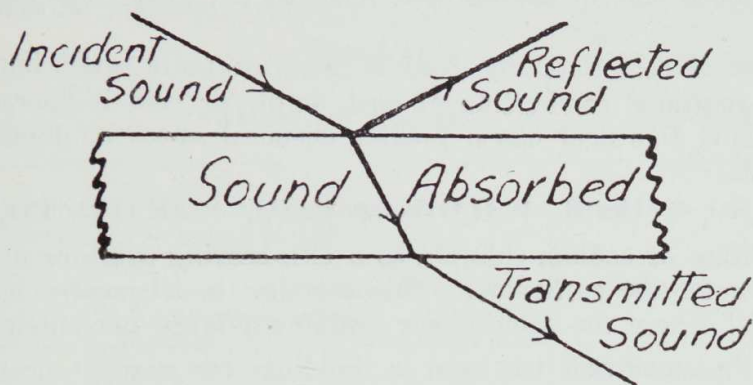


Fig. 8.—Reflection, Absorption and Transmission of Sound.

Absorption of sound by materials is due to porosity, compressibility and elasticity. In building stones porosity is the main factor; in carpets, compressibility; in thin glass, elasticity. Perhaps the most important feature in a building stone of the coastal limestone type is the open nature of the pore spaces. The porosity experiments show that all pore spaces in the stone are in direct communication with the atmosphere, and it is probably on this account that the stone has such a high absorption coefficient.

Table 10 gives the absorption coefficient of various materials, including the Coogee (Hackett) stone.

TABLE 10.
Sound Absorbing Coefficients, Pitch 512.

Material.	Coefficients. per sq. ft.
Open window	1.000
Ventilators	0.750
Coogee stone	0.220
Plaster on wood lath	0.034
Brick wall	0.032
Linoleum	0.030
Glass (single thickness)	0.027
Plaster on tile	0.025
Marble	0.010

Although the Coogee stone is the only stone that has been tested, there should be no doubt that most of the coastal limestone would give high absorption coefficients on account of the open character of the pore system, and it is quite possible that some stones would give better results than the Coogee stone.

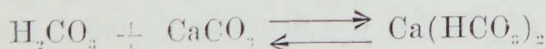
VI.—WEATHERING OF LIMESTONE.*

A—AGENCIES OF WEATHERING.

The weathering of limestone is brought about by chemical and mechanical agencies.

1. Chemical.

Ordinary rain water contains a small amount of carbon di-oxide (CO_2) that it has received from the atmosphere, and is thus a very dilute solution of a weak acid known as carbonic acid (H_2CO_3), which dissolves limestone.



* For detailed accounts of the weathering of building stones, see Howe, 1910, chap. IX., and Merrill, 1910, p. 418.

When other agencies are excluded, the solvent action of carbon di-oxide bearing water is very slow. Hirschwald (1908) experimented on thin slices of limestone exposed to the atmosphere for a definite period and showed that about .00085 mm. of surface was removed per year from the limestone slices.

The effect of rain water by itself is therefore quite small, but in towns, through the continual combustion of coal, sulphuric acid is liberated in the atmosphere, and this acid has a greater chemical effect on limestone than carbonic acid.



The addition of sodium chloride to a CO_2 -bearing solution increases its solvent action on the carbonate. This reaction is frequently encountered near the coast where the atmosphere contains a large percentage of salts.

Coastal limestone that has been in buildings for years is nearly always coated with vegetable organisms such as microscopic algae, lichens and mosses, and decay by organic acids excreted by these organisms, is considered by some writers to be an important chemical effect. Other writers consider that the chemical effect is not great, and that the coating of organic matter protects the stone from the sun's rays and the rain.

2. Mechanical.

The principal mechanical agencies of decay are wind, changes of temperature and frost.

Wind is a powerful agent in hastening the decay of buildings near sea beaches, for wind-blown sand is an effective abrasive in wearing away loosely coherent stones. In addition the effect of a strong wind in driving rain into the interior of porous stones is noteworthy.

The destructive effect of variation in temperature is very important in desert regions where cold nights follow hot days; and the effect is more marked in close than in open-grained stones. The open grain and high porosity of the coastal limestone are therefore desirable features in a stone which is to be subjected to a wide temperature range.

Frost action would probably produce very little, if any, effect on the coastal limestone for it contains a large amount of air space which would allow for the expansion of water when converting to ice. Moreover, heavy frosts are unknown on the Swan Coastal Plain where the limestone is solely used.

Alternate water-logging and drying-out, though injurious to certain types of building stone, appears to have little effect on the coastal limestone.

The destructive effect of insects, such as ants, has not been mentioned, as far as I know, in text-books on building stones, but I have seen, on several occasions, very crumbly coastal limestone foundations of houses, harbouring ants. In this instance open grain is detrimental to the value of a stone for foundation work.

B—RESISTANCE OF THE COASTAL LIMESTONE TO WEATHERING.

During the porosity determination the coastal limestone was subjected to very drastic treatment which consisted chiefly of periodic temperature changes over a wide range on totally dry and on completely waterlogged stones; and consequently a certain amount of material was detached from each block. By weighing the block before and after the experiment the total loss of detachable material was determined, and I think that the percentage loss of detachable material calculated for each stone should give some comparative idea of its resistance to weathering.

The method adopted for the porosity is outlined on p. 28, but to save reference the principal stages are outlined below (Table 11), together with the nature of the changes which occurred and the possible sources of loss of detachable material.

TABLE 11.

Stage.	Nature of Change.	Source of Loss.
1. Drying at 130°C. for 4 hours	Rapid temp. change from room temp. to 130°C.	Expansion
2. Cooling in desiccator	Rapid temp. change from 130°C. to room temp.	Contraction
3. Weighing ...	... ..	Handling
4. Boiling ...	Rapid temp. change from room temp. to 100°C.	Expansion and agitation of block due to convection currents
5. Cooling ...	Slow temp. change from 100°C. to room temp.	Contraction
6. Repetition (twice) of 4 and 5	Repetition (twice) of 4 and 5	Repetition (twice) of 4 and 5
7. Weighing ...	... ..	Handling
8. Redrying at 130°C. for 4 hours	Rapid temp. change from room temp. to 130°C.	Expansion
9. Cooling in desiccator	Temp. change from 130°C. to room temperature	Contraction
10. Weighing ...	... ..	Handling

The percentage loss of detachable material ranges from 0.00 per cent. up to 0.35 per cent., with an average value of 0.16 per cent. Out of thirty-three samples of stone, ten gave values under 0.10 per cent.; thirteen gave values between 0.10 per cent and 0.20 per cent; five between 0.20 per cent. and 0.30 per cent.; and five over 0.30 per cent. Taken individually the value for each stone has no significance, but collectively the values afford a ready means of comparison; and in Table 12 are given the ranges in percentage loss of detachable material for stone from various localities, the average values and the numbers of samples tested.

TABLE 12.

Locality.	Range in Percentage Loss of Detachable Material.	Average Percentage Loss of detachable Material.	No. of Samples Tested.
B (three quarries) ...	0.00—0.16	0.08	7
D (two quarries) ...	0.05—0.33	0.12	7
A (two quarries) ...	0.10—0.19	0.15	4
C (two quarries) ...	0.11—0.35	0.22	4
E (two quarries) ...	0.18—0.31	0.25	6

There is no relationship, as far as I can see, existing between the percentage loss of detachable material and porosity, insoluble content, character of the cement or texture, but it is significant to note that in general, the samples obtained from quarries containing stone of variable quality, invariably lose a fairly large amount of material during the porosity determinations. It is also significant that most of the stone from the localities C and E has a porosity of over 50 per cent. and an average percentage loss of detachable material of over 0.20 per cent.

It is reasonable to assume that, in general, highly porous stone of a variable quality should weather more easily than stone of even quality and low porosity, for I consider that to some extent the amount of material lost during the porosity determinations does give an indication of the resisting power of a stone to weathering. Furthermore, the average values given in Table 12 accord fairly well with my field and laboratory observations concerning the quality of the stones and their weather-resisting powers. Such observations are of a general character and are based not on individual samples but on a number of samples and on the nature of the particular quarry from which they were obtained.

The examination of stones taken from the walls and foundations of old buildings (*e.g.*, 9395, 9396, and 9400 to 9403), and also of a stone (9398) taken from the sea-wall at North Fremantle, where it had been for over 60 years, shows that they have stood the test of time remarkably well. 9398, originally from quarry No. 9, loc. D, is very similar to 9397, which was collected from the same quarry in 1929. It is interesting to note that 9398 gave exceptionally high compressive strength values—the highest (as far as I know) yet obtained for the coastal limestone. Of the stones taken from old buildings, 9395 and 9396 (originally from the same quarry as 9397 and 9398), and 9402 and 9403 (quarry not known), compare favourably with similar types of stone recently collected from the various quarries. 9400 and 9401 are exceptional (being the only representatives of Textual Type 3), and cannot be compared with other stones.

C—INDURATION OF STONE ON EXPOSURE.

That the coastal limestone hardens on being removed from the quarry, or when exposed in an old quarry face, is well known to contractors and stone-masons. The reason for this is that the stone holds a certain amount of water containing lime carbonate in solution or suspension, and when this "quarry water" is drawn to the surface of the stone by capillarity, and evaporation takes place, the lime carbonate is deposited on the surface of the stone as a thin film, which helps to bind the grains more closely together, and prevents to some extent the entrance of rain water into the stone. The crust so formed is necessarily very thin and, according to Merrill (1910, p. 432), when once it is destroyed it can never be replaced. Shaping of the stone, according to him, should therefore be done before it is put into place and while it still contains the quarry water. If the shaping is done after the stone is set in position, the thin crust of lime carbonate will probably be removed and the stone will be less resistant to weathering than it would be if the crust were not removed.

Old cuttings or quarry faces frequently show the indurated crust, and one of the best examples is an old cutting, Quarry No. 11, locality E.

Merrill states that the indurated crust can never be replaced, but from observations over a period of three years, on a block of stone from the above-mentioned quarry (No. 11, loc. E), I think that the coastal limestone develops a hardened surface in summer which it partly loses in winter. Of course it must be remembered that this limestone is an exceptional type of building stone, particularly so because of its high porosity.

VII.—ORIGIN OF THE COASTAL LIMESTONE.

It is believed by most local geologists that much of the coastal limestone is of dune origin, but no detailed investigations have been made to prove whether this is or is not so. However, although this paper is entirely concerned with the economic aspect of the stone, it is worth while to record briefly, certain observations obtained from field and laboratory investigations, which may explain the processes by which the various types of stone have been produced.

There are, between Balcatta and Coogee, numerous quarries, any one of which may belong to one of two types—juvenile or mature. The characteristics of these types are given on p. 19. The terms “juvenile” and “mature,” which I have borrowed from physiography, denote two extreme stages in the development of the bedded stone and the network evidently derived from it. Intermediate stages can be observed in several quarries. For example, in the juvenile quarry, No. 7, locality C, there are in places small networks. However, the characteristics are predominately those of a juvenile quarry, and the quarry is consequently classified as juvenile. Conversely in a mature quarry there may be patches which are juvenile in character, but they are relatively insignificant, and the quarry is therefore considered as being mature. The amount of network in a quarry is the criterion by which the quarry is classified.

Large pipes (or trunks) may be present in both types of quarry irrespective of whether network is or is not present. In quarry No. 4, locality B, for example, there are numerous large pipes which appear to be downward extensions of the capstone, but no network is present. On the other hand, both network and pipes can be seen in quarry No. 8, locality D.

From the petrographic examination of a large number of stones one fact is fairly obvious—that is, the cementing material is of secondary origin. This suggests that the limestone was originally a current bedded deposit of loose sand—probably beach sand.

It is now possible to trace the history of the various materials (*i.e.*, capstone, pipes, network and bedded stone) constituting the limestone. My interpretation is as follows:—

The material which originally gave rise to the coastal limestone was in the form of a sand dune. If it were possible to cut a section through the dune it would be seen that the material was loose beach sand (composed of quartz grains and shell fragments) and that it was current bedded. Near

the surface of the dune there would be a fairly large amount of vegetable matter in the form of matted roots, which represented either living plants or ones which had been buried in the sand.

Rain falling on such a dune would eventually effect the cementation of the closely packed grains. The presence of salts and weak acids in the rain water would cause the shell fragments to dissolve slightly, and on removal of the water, thin films of chemically precipitated carbonate would be left on their surfaces. (There are numerous examples of stones of this type, particularly ones containing only very small percentages of insoluble material.) Some of the dissolved carbonate would probably be removed in solution and redeposited close-by (on the frosted surfaces of quartz grains) or carried downwards by gravity or upwards by capillarity (thus accounting for the capstone), the depth from the surface and the climatic conditions governing to some extent the upward movement due to capillarity.

This represents the juvenile stage in the development of the limestone.

Finally, by the continual dissolving of the shell grains and redeposition of carbonate elsewhere, the mature stage would be reached. The bedded stone some distance below the surface would be probably no different from similarly situated stone at the juvenile stage of development, but near the surface certain changes would be noticed. Around the organic matter present in the surficial layers calcium carbonate would be precipitated, and by the passage of circulating solutions, downward by gravity and upwards by capillarity, a network would be formed, consisting of tubes of calcium carbonate and interstitial loose material. The bedded stone just below the network would be extremely porous, and the small delicate shells such as foraminifera would completely lose their identity.

Petrographic observations on stones collected from different depths in juvenile and mature quarries support the ideas mentioned above. In the juvenile quarry the quality of the stone is fairly uniform throughout, irrespective of the depth from which the samples are obtained. On the other hand in the mature quarry porosity values as high as 55 per cent. are obtained from stone just below the network, while stone some distance below the network may give values under 40 per cent.

Stone of uniform quality may be obtained from both types of quarry, but in the mature type it is necessary to select the stone carefully, on account of the network and the highly porous bedded stone immediately underlying it. In the juvenile type there is less need of careful selection for most of the stone is uniform in quality and it is only necessary to discard the bedded stone containing organic matter, which, in the few quarries I have seen, is only a few feet in thickness.

Concerning the origin of the large pipes, or trunks, I feel hesitant in expressing an opinion, for I have not seen very many of them and have not studied them in detail. In quarry No. 4, locality B, there are several large pipes which appear to be downward continuations of the capstone. The fact that they are essentially vertical seems to suggest that their formation has been controlled by gravity, and that they have thus developed from the surface downwards. The stone from this quarry is extremely hard and it has a very low porosity.

VIII.—SUMMARY.

About forty samples of limestone suitable for building purposes were obtained from various quarries between Balcatta and Coogee on the Swan Coastal Plain, and were examined in the laboratory. The principal characters and properties of the stone are as follows:—

Colour—Pale ash-grey, white, cream, buff.

Constituents—Quartz grains and carbonate grains (many of which are definite shells or shell fragments) cemented by calcium carbonate. The cement is believed to have been derived from the carbonate grains by the process of solution and redeposition. The amount of acid insoluble material in the stone varies from 5 per cent. to 66 per cent. This variation is influenced by the grain size, for in most of the medium and coarse grained stones the largest grains are of quartz.

Texture—The stones vary considerably in grain size. There are fine, medium and coarse grained stones with average grain sizes of 0.2 mm., 0.5 mm. and 1.0 mm. respectively. In some stones the grains are packed closely together; in others they are fairly widely separated. The cement varies in quantity and distribution. In some stones it occurs as thin films surrounding the carbonate grains from which it has been derived; in other stones it is very patchy, being particularly thick around quartz grains. The cement never completely fills the spaces between the grains, and consequently the stone is characterised by a high porosity. The wide range in porosity, 17 per cent. to 57 per cent. (average about 40 per cent.), is due to texture and is entirely independent of mineral composition.

Compressive Strength—The compressive strength depends largely on the porosity, insoluble content and grain size, porosity being the principal factor. Values obtained vary from less than 10 tons per square foot up to 318 tons per square foot, but most of the stones commonly used (those with porosity values exceeding 40 per cent.) give values less than 50 tons per square foot.

The coastal limestone includes, in addition to the bedded stone used for building purposes, several materials which have been referred to as cap-stone, large pipes and network. Quarries free of network are called juvenile quarries, while those containing a large amount of network are referred to as mature quarries.

Most, if not all, of the coastal limestone is considered to be of dune origin and is regarded as belonging to the Recent Period of the Cainozoic Era.

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TABLE 13.

Locality.	Quarry.	Catalogue Number.	Porosity (percentage volume of air space).	Bulk Density.	Weight (lbs./cubic foot).		Density of Rock Material. §	Compressive Strength. (tons/sq. ft.)	Insoluble Content (percentage by weight).	Percentage Loss of Detachable Material during Porosity Determination.	Textural Type.	Compressive Strength Type.	Degree of "Hardness."
					Maximum (water-logged).	Minimum (dry).							
A.	1	9223 (a) 9223 (b)	41.0 42.5	1.59 1.56	125.0 124.0	99.4 97.5	2.70 2.71	} average 26.7 {	32.70 31.14	0.17 0.19	2b 2b	A5 A5	Medium do.
	2	9389 9390	41.8 43.7	1.56 1.51	123.6 121.7	97.5 94.4	2.69 2.69	} average 28.6 {	49.63 38.09	0.10 0.14	2b 2b	A5 A5	Medium do.
B.	3	9391 9392 A'age of sev- eral samples	40.2 48.5 46.0	1.63 1.39 1.43	127.0 117.2 118.1	101.9 86.9 89.4	2.72 2.70 —	} average 26.5 {	15.06 16.80 16.00	0.06 0.02 —	1b 1b 1b	A5 A5 A5	Medium do. do.
	4	9227 9226 9225 9224	17.9 31.6 35.0 39.7	2.24 1.86 1.77 1.63	152.4 136.0 132.5 126.7	140.0 116.3 110.6 101.9	2.72 2.72 2.72 2.71	Estimated at over 150 ... Estimated between 100—150 Estimated 50—75 ... Estimated 30—75 ...	8.12 11.54 15.62 14.62	0.00 0.16 0.10 0.11	1a 1a 1a—b 1a—b	A1 A2 A4 A4	Very hard do. Hard do.
	5	9399	37.4	1.69	129.0	105.6	2.73	59—111 ...	14.37	0.04	1a—b	A4	Hard
	6	9235 9236	55.3 50.9	1.22 1.33	110.8 114.9	76.3 83.1	2.72 2.71	Estimated at under 20 ... ,, ,, 20 ...	11.98 16.45	0.35 —	1b 1b	A5 A5	Very soft do.
	7	9237 9238 9239	39.2 43.6 56.8	1.65 1.53 1.17	127.5 122.9 108.6	103.1 95.6 73.1	2.72 2.72 2.72	Estimated 25—50 ... Estimated under 30 ... ,, ,, 20 ...	24.20 28.65 15.93	0.13 0.11 0.27	1a 1b 1b	A4—5 A5 A5	Soft—medium Soft Very soft
D	8	9385 9386 9387 9388	51.0 47.0 45.7 41.4	1.32 1.43 1.46 1.57	114.4 118.7 119.8 124.0	82.5 89.4 91.3 98.1	2.70 2.69 2.69 2.68	Estimated under 20 ... ,, ,, 30 ... ,, ,, 30 ... ,, ,, 40 ...	28.76 31.62 33.44 28.57	0.07 0.05 — 0.05	1b 1b 1b 1b	A5 A5 A5 A5	Soft Soft—medium do. do.
	9	9395† 9396† 9397 9398‡	29.8 41.2 25.6 23.6	1.88 1.59 2.03 2.08	136.1 125.1 142.9 144.8	117.5 99.4 126.9 130.0	2.68 2.70 2.72 2.72	79—113 ... 34—52 ... 129—143 ... 150—318 ...	25.44 18.15 16.25 19.67	0.33 0.05 0.12 0.18	2a 2b 2a 2a	A2—3 A5 A2 A1	Hard Soft—medium Hard—very hard Very hard
	10	9228 9229 9230	34.8 53.2 54.7	1.77 1.26 1.22	132.4 112.0 110.4	110.6 78.8 76.3	2.71 2.70 2.70	Estimated 50—75 ... Estimated under 30 ... ,, ,, 30 ...	10.81 7.85 8.42	0.24 0.22 0.18	1b 2b 1b	A4 A5 A5	Medium Soft do.
	11	9231 9232 9233	45.1 38.8 40.8	1.48 1.66 1.60	120.7 128.0 125.5	92.5 103.8 100.0	2.70 2.70 2.70	Estimated under 50 ... ,, 50—75 ... ,, under 50 ...	21.08 17.04 21.34	0.31 0.27 0.28	1b 1b 2b	A5 A4 A5	Medium do. Soft—medium
	12	10486	39.5	1.63	127.0	102.0	—	Estimated under 50 ...	24.12	—	—	—	—
Taken out of the wall of an old building	...	9400 9401 9402 9403	36.5 35.2 49.7 32.8	1.69 1.73 1.36 1.80	128.4 130.1 116.0 133.0	105.6 108.1 85.0 112.5	2.66 2.67 2.69 2.68	11.7* ... 23—41 ... 12—14 ... 65—70 ...	61.20 66.81 18.67 30.31	0.31 0.16 0.34 0.17	3 3 1b 2a	A5 A5 A5 A4	Soft Medium, crumbly Soft Medium—hard
Garden Island ...	...	9393	25.1	2.03	142.6	126.9	2.73	Estimated over 150 ...	4.57	—	1—2a	A1	Very hard
Hamelin Bay ...	...	8825	35.1	1.77	132.5	110.6	2.73	Estimated 50—100 ...	Not determined, estimated under 2 per cent.	0.11	2a	A3—4	Hard

* This sample had an initial fracture and was not square.

† Taken out of the wall of an old building, but were originally obtained from quarry No. 9.

‡ Taken from the sea-wall at North Fremantle,

where it had been for 60 years (originally from quarry No. 9).

§ Calculated from porosity data; inserted here only as a check on the porosity determinations.

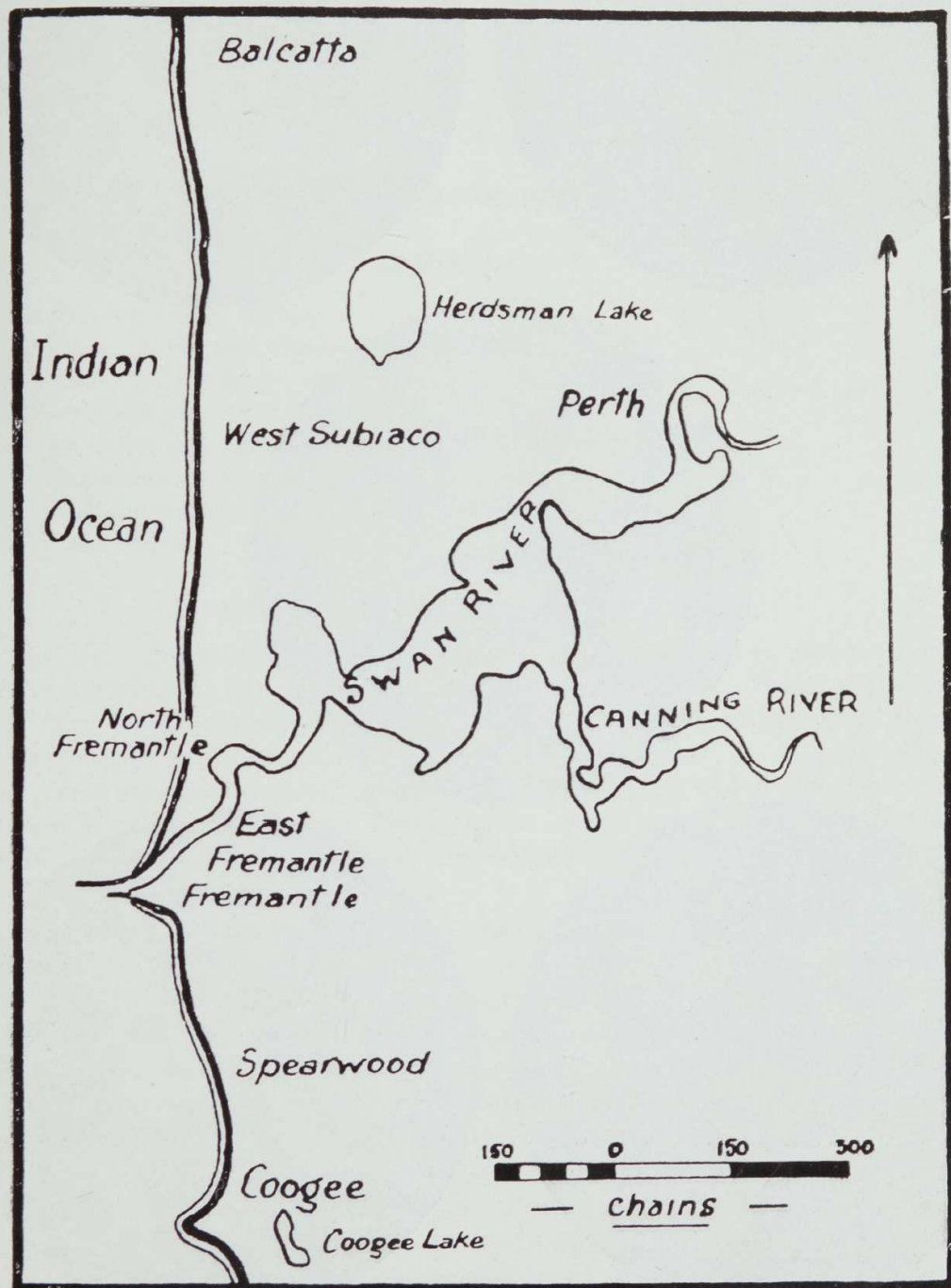
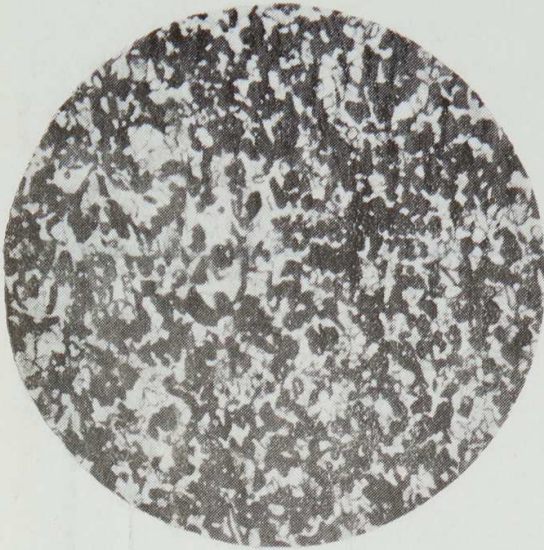
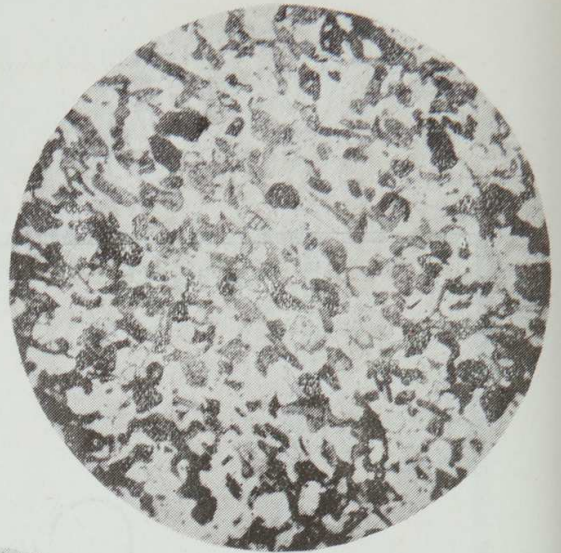


Plate I.



1a



1b



3



2a



2b

× 12

PLATE II.

Photomicrographs illustrating Textural Types.

- 1a, 9237 Quarry No. 7, locality C.—Black portions represent carbonate grains. Quartz grains and air-spaces appear colourless.
- 1b, 9235 Quarry No. 6, locality C.—Black and dark grey portions represent carbonate grains; quartz grains are light grey and colourless; air-spaces are colourless.
- 2a, 9398 Quarry No. 9, locality D } The constituents and air spaces have the same
- 2b, 9223 Quarry No. 1, locality A } colouring as in 1b.
- 3, 9400 Taken out of an old building. Colourless grains are quartz; black grains are carbonate. The cement embedding the grains is porous, the black patches representing cement and the colourless patches air-spaces.

Photo. H. Smith.